RADIOFREQUENCY RECOMBINATION LINES FROM THE INTERSTELLAR MEDIUM

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Abstract

A selective discussion is given of observations of recombination lines from "normal" H II regions, extended H II regions, nonthermal sources, and the H I medium. Detection of recombination lines from elements other than hydrogen may provide a means of identifying "fossil Strömgren spheres" at high temperature.

I. Introduction

The capture of an electron by an ion into a highly excited level (principal quantum number n $\gtrsim$ 60) and the subsequent cascade to the ground term can produce line emission in the radiofrequency portion of the spectrum. The emission frequency is given by $\nu = cRZ^2 [n^{-2} - (n + \Delta n)^{-2}]$ where R is the Rydberg constant for an element of charge Z. When $\Delta n = 1$, the transition is denoted as an α-transition; when $\Delta n = 2$, a β-transition; etc. Such lines are observed in the spectra of H II regions, where transitions over a wide range in principal quantum number, n = 57 → 56 (56α) at 36.5 GHz to n = 254 → 253 (253α) at 400 MHz, have been detected from hydrogen (Sorochenko et al. 1969; Penfield et al. 1967). Higher order transitions, involving a change in principal quantum number greater than one, have also been observed up to $\Delta n = 5$ (so-called ϵ-transitions). The strongest recombination lines found to date are those of hydrogen; lines from helium are present if the excitation of the H II region is sufficiently high, but the intensity is about a factor of 10 less than that of hydrogen because of the lower helium abundance. Narrow recombination lines observed in the spectra of H II regions appear to be formed in H I clouds between the source H II regions and the observer.

Study of recombination lines has extraordinary value. They can be used as diagnostic tools in determining the physical parameters of the emitting region: radial velocity, electron temperature, electron density, turbulent velocity, and emission measure. In addition, the fractional ion concentration can be derived from intensity ratios of two lines originating in the same region and produced by different elements.

In the following sections we note selected results on studies of recombination lines from thermal and nonthermal sources and suggest observations that may be useful in studying "Gum Nebulae" and related objects.

II. Thermal Sources

A. Normal H II Regions

To understand how recombination lines vary in different sources, it is useful to briefly describe the solutions to the transfer equation for the line and continuum intensities in a normal H II region. Here ionization results from the ultraviolet radiation field of nearby exciting stars. Recombination takes place via radiative processes also, and the high levels of atoms producing recombination lines are not populated in equilibrium at the local electron temperature. The continuum emission however is due to thermal bremsstrahlung. The line-to-continuum ratio for a recombination line formed by a transition from upper level m to lower level n in an isothermal, homogeneous, optically-thin gas is given by

$$\frac{T_L}{T_C} = \frac{\tau_L^*}{\tau_C}\left[b_m - \frac{1}{2} b_n \beta_{nm} (\tau_C + b_m \tau_L^*)\right] \tag{1}$$

where the optical depths in local thermodynamic equilibrium (LTE) of the line and continuum are given by τ_L^* and τ_C (Dupree and Goldberg 1970). The non-LTE departure coefficient for level n is denoted by b_n, and the correction factor for stimulated emission is given by (Goldberg 1966)

$$\beta_{nm} = \frac{b_m}{b_n}\left[1 - \left(\frac{k\,T_e}{h\,\nu}\right)\left(\frac{b_m - b_n}{b_m}\right)\right]. \tag{2}$$

In H II regions where $T_e \sim 10^4$ °K, the b factors for hydrogen and helium for $n \sim 100$ are less than but approximately equal to one. The quantity β can be negative and have an absolute value much greater than one owing to the amplification of small population differences between levels by the factor $kT_e/h\nu$. Inspection of equation (1) shows that the line intensity depends on the value of the upper level population as expected ($b_m \equiv 1$ in LTE) and on the amount of stimulated emission due to both the continuum and the line self-emission. If the atomic levels are populated in LTE, the line-to-continuum ratio for $n\alpha$ transitions ($\Delta n = 1$) is given by

$$\frac{T_L}{T_C} \simeq \frac{2.33 \times 10^4 \, Z^2 \, \nu^{2.1}}{\Delta \nu_L \, T_e^{1.15}} \left(\frac{E_L}{E_C}\right) \exp{(X_n)} \tag{3}$$

where $Z = (m + 1)$ for an atom X^{+m}; ν (GHz) is the frequency of the transition; $\Delta\nu_L$(kHz) is the full line width at half-power; (E_L/E_C) is the ratio of the emission measures of the line and the continuum ($E_L/E_C \cong 0.91$ for H II regions); and $X_n = 157800\ Z^2/n^2 T_e$.

The H109α transition at 5 GHz has been surveyed in sources in both the northern and southern hemispheres (Reifenstein et al. 1970; Wilson et al. 1970). The line-to-continuum ratio in H II regions varies from 2 to 22 percent and averages about 5 percent. The southern survey has included observations of three sources which happen to lie within the extended boundaries of the Gum Nebula, as noted by Abt et al. (1957); G265.1+1.5; G267.8-0.9; G268.0-1.1. One of the sources, G267.8-0.9 (RCW 38), has been mapped at 5 points in the H109α and H126α, H127α transitions (McGee and Gardner 1968; Wilson 1969). All three show a continuum spectrum indicative of an optically-thin thermal source (Milne et al. 1969). The LTE electron temperatures determined by substitution in equation (3) range from 6000-7900 °K; however, such LTE values usually underestimate the actual temperature in H II regions.

To determine the parameters of line-emitting regions, observations are needed at many frequencies and should include higher order transitions as well. Several methods (Hjellming and Davies 1970; Goldberg and Cesarsky 1970) are being used to obtain the parameters of H II regions. These rely on observations at a number of frequencies to determine the emission measure E, T_e, and n_e (see Table 1). Unfortunately, only the brightest H II regions have been studied in such detail, and the emission measures are probably not representative of H II regions generally. H II regions in the surveys have $E \gtrsim 10^4$ pc cm^{-6}; NGC 7000 and the Rosette Nebula appear to be among the H II regions of lowest emission measure (<10000 pc cm^{-6}) in which a recombination line has been detected (Dieter 1967); Penfield et al. 1967). Clearly "normal" H II regions can be profitably studied with recombination line measurements of hydrogen at various frequencies and at several points within the nebula.

A helium line is present in many H II regions if there are ultraviolet photons of sufficient energy available to ionize neutral helium. At temperatures of 10^4 °K, we expect the departures from LTE for high levels of the helium atom to be the same as for hydrogen. Hence, with the assumption of well-mixed emitting regions, the ratio of line energies $T_L \Delta\nu_L$ for corresponding helium and hydrogen transitions gives directly the ratio of ion densities n_{He^+}/n_{H^+}. Assuming the helium to be all in the form of He II, Palmer et al. (1969) find an average value 0.084 of the helium abundance in H II regions.

Table 1
Parameters of H II Regions

Object	n_e (cm^{-3})	T_e (°K)	L (pc)	EM (pc cm^{-6})	Ref.
"Normal" H II Regions					
Orion	17000	10000	0.066	1.9×10^7	1
M8	4900	7700	0.042	1.0×10^6	2
M17	16000	7500	0.063	8.2×10^6	1
W51	44000	10000	0.028	5.5×10^7	2
NGC 7000	~10	~10000		$2-8 \times 10^3$	7,8
Supernova (H II Region)					
Gum Nebula	0.2	~57000	800	3×10^1	6
Tycho Model I	1.	80000	190	2×10^2	3
Tycho Model II	0.1	100000	260	2.6	3
Tycho Model III	10.	27000	20	2×10^3	3
Supernova (Filament)					
Gum Nebula	~300	10^4-10^5	0.03	$\sim 1.3 \times 10^3$	6
Cygnus Loop (O III)		$\sim 10^5$	0.01-0.02		4,5
Cygnus Loop (O II, S II, N II)	80-400	15000-20000	0.01-0.02	10^2-10^3	4,5

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B. Fossil Strõmgren Spheres

Recent theoretical and observational results suggest (Brandt et al. 1971; Morrison and Sartori 1969) that there may also be large H II regions that have been ionized by ultraviolet or x-ray radiation or by cosmic rays associated with supernovae. Physical conditions in these regions – so-called fossil Strõmgren spheres – at early stages of their evolution could differ markedly from conditions in a normal H II region. Some representative parameters included in Table 1 show that the electron temperatures may reach 10^5 °K, while the electron density can be 10 cm^{-3} or less (Kafatos and Morrison 1971).

It is interesting to speculate on the recombination line spectrum from such a configuration. Such conditions of high temperature and low density lead to strong departures from LTE conditions in the populations of high levels. In particular, certain atoms and ions of abundant heavy elements (such as helium, oxygen, or carbon) can experience severe overpopulation of high levels (Goldberg and Dupree 1967) that may lead to greatly enhanced intensities of radiofrequency recombination lines. This can result from an increased b_n and/or β factor [see equation (1)] as compared to the values for hydrogen. The He II atom, for instance, recombines to He I predominantly by dielectronic recombination at temperatures $\gtrsim$ 50000 °K. Calculations of high level populations of He I for electron densities of 10^4 cm^{-3} show that overpopulation of levels n $\sim$ 40 leads to b_n $\sim$ 100 at T $\sim$ 10^5 °K (Burgess and Summers 1969); preliminary estimates for lower densities of n_e $\sim$ 1 cm^{-3} at T $\sim$ 80000 °K indicate that b_n > 100 at n $\sim$ 100. By contrast, hydrogenic atoms recombine directly onto a singly-excited level by radiative recombination, a process that usually proceeds more slowly than dielectronic recombination. And the departure coefficients, b_n for hydrogenic atoms are close to, but less than one. Thus if helium is in the singly ionized state (He II) in a high temperature medium, a recombination line of He I may very well be stronger than the corresponding hydrogen transition. Recombination lines from atoms populated by dielectronic recombination will have a frequency dependence that differs from that of lines arising from hydrogen. The hydrogen-to-helium line ratio should not be constant with n as it is at temperatures near 10^4 °K. With increasing n, it is possible that the emission line will turn into an absorption line when the b_n factors decrease as the levels approach their LTE populations and β becomes positive [see equation (2)].

Ions such as O II and O III can also experience overpopulations (b > 1) of high levels at T $\gtrsim$ 40000 °K. However, detailed calculations are required to see whether the b_n and β factors are sufficiently large to compensate for the oxygen abundance and to make the line intensities comparable to those of hydrogen and helium. At present, calculations for high temperatures are available for only a few neutral atoms and ions (Dupree 1969; Burgess and Summers 1969).

In the proposed fossil Strömgren spheres, helium may be completely ionized, in which case recombination lines from He II would be produced. We do not expect enhancement of high level populations in the He II atom because dielectronic recombination is not possible; however, the behavior of the b_n factors will differ in detail from that of hydrogen, because of a charge dependence of atomic parameters such as collision cross sections and radiative lifetimes. Detection of recombination lines from He II would be of particular interest because the character of the ionization source may well be inferred from its presence.

III. Nonthermal Sources

A small proportion of sources observed at H109α in the northern and southern surveys displayed a nonthermal continuum spectrum. The hydrogen line in such sources is weaker than in most normal H II regions (Milne et al. 1969; Wilson and Altenhoff 1969). This apparent weakness can result from a number of conditions. The electron temperature may be higher in a nonthermal source than in an H II region. Evaluation of equation (1) shows that if the H109α line has a value of T_L/T_C that equals 5 percent at 10000 °K, its intensity will decrease to 2 percent at 20000 °K. Alternately, a nonthermal contribution to the continuum intensity will also cause the line to appear weaker than normal. In addition, the level populations may be affected by a strong nonthermal continuum. Stimulated emission can also be enhanced by the continuum. Details of the effect of a nonthermal continuum source upon atomic level populations and line intensities have not yet been investigated. It is possible too that in a nonthermal source a recombination line may be excessively broadened by turbulent velocity; this possibility should be verifiable if optical observations of forbidden-line emission are available.

Several searches have been made for recombination lines in two supernova remnants. The Cygnus Loop was searched at H158α and C158α (Downes 1970), and Cas A at H166α and C166α (Zuckerman and Ball 1970); both attempts were unsuccessful. However, a recent study of the supernova remnant W 28 shows an admixture of thermal and nonthermal sources with detectable recombination lines at H109α (Milne and Wilson 1971).

If the high temperature and a nonthermal background are the principal reasons for the weakness of recombination lines in nonthermal sources, it would appear that investigations at high frequencies are an optimum choice for several reasons: the line-to-continuum ratio increases with increasing frequency (equation 3); the nonthermal continuum makes less of a contribution relative to a thermal continuum at high frequencies; a smaller beamwidth may minimize the nonthermal contribution to the measured continuum temperature.

IV. The H I Component

The detection of recombination lines from cold clouds (Ball et al. 1970; Gottesman and Gordon 1970) is potentially one of the most powerful diagnostics of the neutral hydrogen component of the interstellar medium. Transitions from both carbon and hydrogen have been observed (Palmer et al. 1969; Ball et al. 1970). The detection of corresponding transitions in two elements allows the ratio of ionized fractions to be determined directly from the ratio of energy in the line, viz:

$$\frac{(T_L \, \Delta \nu_L)_H}{(T_L \, \Delta \nu_L)_C} = \frac{n_H^+}{n_C^+} = \frac{n_H^+/n_H}{n_C^+/n_H} \, . \tag{4}$$

In this case, carbon is believed to be fully ionized by the local radiation field because its ionization potential is less than that of hydrogen. The carbon abundance is assumed to be known, and carbon and hydrogen are taken to be well mixed in the line-forming region. Hence, such observations lead directly to the degree of hydrogen ionization. The quantity n_{H^+}/n_H has been found to equal 2.7×10^{-4} in one cloud along the line of sight to NGC 2024 (Ball et al. 1970).

Observations of the carbon line at several frequencies, when combined with calculations of the line intensities, are expected also to yield values of (or at least constraints on) other physical parameters of H I clouds. Recent theoretical results indicate that atomic populations of high levels can be modified by thermal radiation fields similar to those observed in H II regions. Hence, detailed models of the cloud configurations may be needed.

Detection of similar lines from the "hot" H I component may allow one to discriminate among various models of the interstellar medium. In particular, the degree of ionization of helium as compared with hydrogen is greater for models heated by X-rays or UV radiation than for models with energetic particle heating (Jura and Dalgarno 1971; Bergeron and Souffrin 1971).

Search for recombination lines from neutral hydrogen requires knowledge of the 21-cm profiles near the source, so that corresponding radial velocities may be searched with appropriate velocity resolution. Observations indicate that the carbon line (formed in cold H I clouds) becomes stronger at lower frequencies relative to lines originating in H II regions (Churchwell 1969). This suggests that low frequencies are most appropriate for its detection in order to facilitate separation of an H I and H II profile. However, some consideration must also be given to the size of the beamwidth to ensure that the signal from the H I region is measurable against an extended background H II region or nonthermal source.

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